Millimeter-wave measurements of energetic-ion driven ion cyclotron harmonic waves in DIII-D

by

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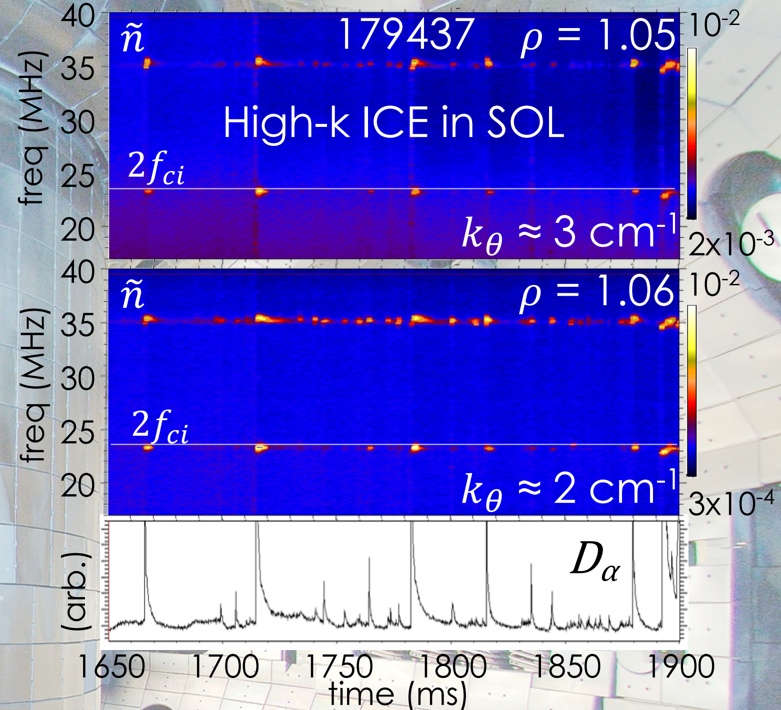

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Ion cyclotron range fast-ion driven instabilities may cause thermal transport & be used for fast-ion diagnosis

- **Ion cyclotron emission (ICE) at f_{cb} harmonics frequently observed, typically with beam heating or significant fusion products**
  (see e.g. reviews [K. McClements, NF 2015; N. Gorelenkov, New J. Physics 2016])
- **Leading theory: ICE driven by Doppler-shifted cyclotron resonance with fast ions – aka magnetoacoustic cyclotron instability (MCI)**
  [V.S. Belikov, Sov. Phys. Tech. Phys. 1976, R. Dendy, PoP 1994 p. 1918]
  - drive from distribution gradient w/resp. to $\boldsymbol{v}_\perp$ (anisotropy)
  - fast Alfven waves ($k_\perp \rho_f \ll 1$) & cyclotron harmonic waves ($k_\perp \rho_f \gtrsim 1$)
- **Alternatives must be considered – e.g. drift loss cone instability, electrostatic instabiliiies – must learn to distinguish from MCI**
  [TFR Group, PRL 1979 and refs therein; Dendy, PoP 1994 p. 3407 and refs therein; Stix Waves in Plasmas 1992, p. 436; Farmer, Nucl. Fusion 2016]
- **MCI waves may cause thermal transport or "energy channeling"**
  ([Y. I. Kolesnichenko, NF 2020] and Refs. therein)
- **"spectroscopy" using MCI waves constrains inferred fast-ion energy spectrum/spatial distribution**
  - Indicates presence of resonant ions and anisotropy at resonance

Key Results

- Doppler Backscattering (DBS) measurements show ICE $\tilde{n}$ at $2f_{ci}$ & $3f_{ci}$ in the edge of DIII-D plasmas, at the top of the pedestal and in the SOL.

- The observed ICE $\tilde{n}$ is shown to be high-k cyclotron harmonic waves or electrostatic waves

- The ICE $\tilde{n}$ is shown to be radially extended, consistent with eigenmode or propagating wave

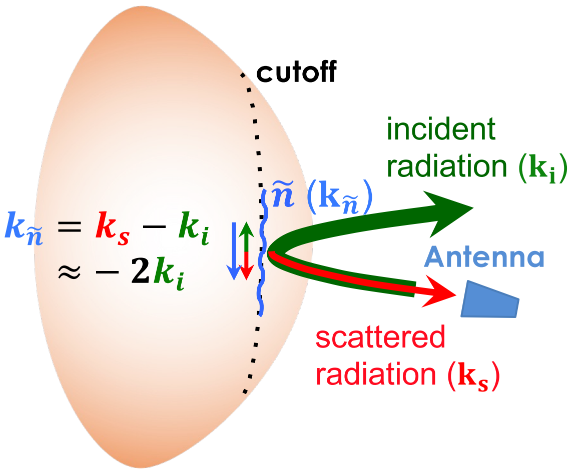
- The stability of the ICE $\tilde{n}$ is influenced by ELMs consistent with drive by fast-ions and fast-ion ejection by ELMs

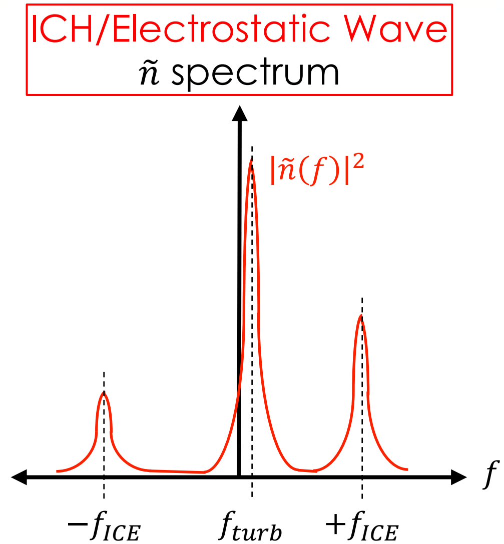
Measurement technique

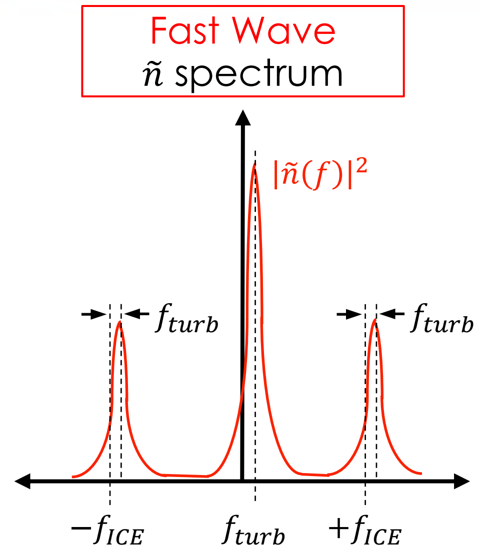
Ion cyclotron range fluctuations measured with two instruments

- **DBS system measures $\tilde{n}$;**
  recently modified to extend frequencies to ion cyclotron range
  - 8 frequency DBS system: 55 – 75 GHz [W. A. Peebles, RSI 2010]
    - Core to edge depending on equilibrium n_e and B profiles
  - modified to split signals into low (LF) and high (HF) frequency bands using diplexer
  - HF DBS potentially sensitive to $\tilde{n}$ with $f \approx 16 - 75$ MHz
- **Array of loops on wall measures edge ion cyclotron range $\tilde{b}_\phi$ (1 – 200 MHz)**
  - for results reported here, see [K. E. Thome, RSI 2018]
  - for recent upgrades enhancing ICE structure measurement capability, see [G. H. DeGrandchamp, RSI 2021] - $\tilde{b}_\theta$ added

DBS system measures ICE $\tilde{n}$ via scattering of mm-waves from plasma waves







- **DBS => $\tilde{n}$ measured via scattering in two ways:**
  1) Fast wave: low-k (k_θ << 1 cm^{-1}) mode ($f = f_{ICE}$) modulates turbulence spectrum ($f = f_{turb}$) $\Rightarrow$ sidebands: $f_{\tilde{n}} = f_{turb} \pm f_{ICE}$
  2) Ion cyclotron harmonic (ICH) or electrostatic wave: high-k mode (k_θ ~ 1 – 10 cm^{-1}) scatters mm-wave: $f_{\tilde{n}} = +f_{ICE}$ or $-f_{ICE}$
     - propagating wave makes peaks at $f > 0$ and $f < 0$ asymmetric
- **Scattering governed by Bragg rules: $\omega_s = \omega_i + \omega_{\tilde{n}}$ and $\mathbf{k}_s = \mathbf{k}_i + \mathbf{k}_{\tilde{n}}$**
  – $\omega_{\tilde{n}} \ll \omega_i, \omega_s \Rightarrow \mathbf{k}_{\tilde{n}} \approx -2\mathbf{k}_i$

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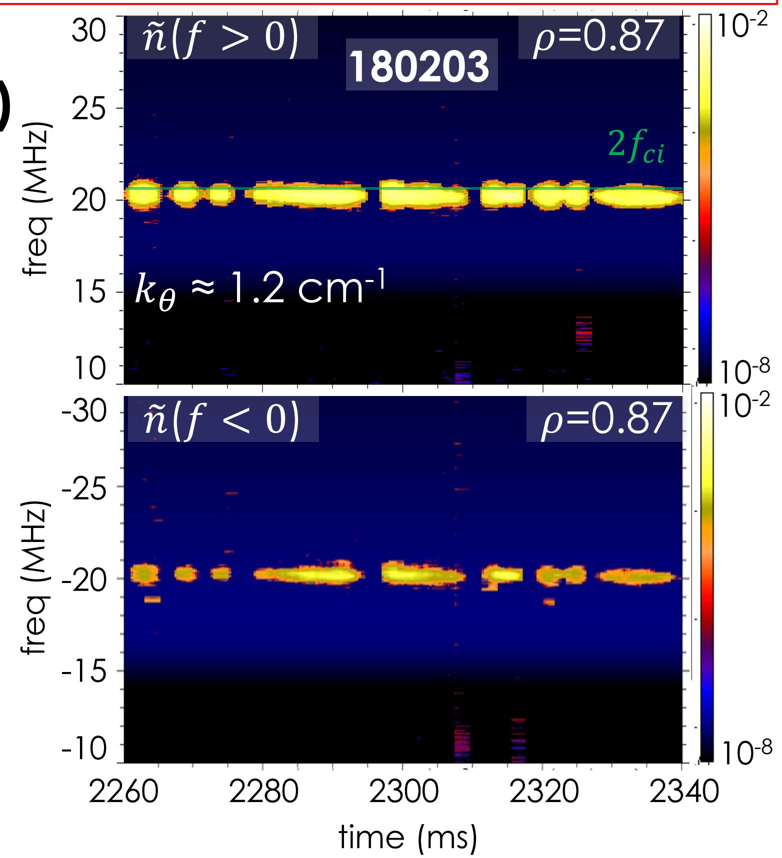
Ion cyclotron emission observations

2nd harmonic ICE high-k observed at top of pedestal in H-mode

- **Deuterium H-mode, reverse B_T**
  - R_{midout} = 2.23 m, R_0 = 1.81 m
- **$\tilde{n}$ measured at ρ = 0.87 (@ pedestal top)**
- **$\tilde{n}$ peaks at ~ ±20.5 MHz ~ ± $2f_{ci}$**
  - f_{ci} ≈ 10.3 MHz, v_A ~ 3.4 x 10^6 m/s
  - ρ_{fast} ~ 3 – 4 cm (species: D)
  - f exactly matches $2f_{ci}$ just outside ρ = 1
- **Peaks are caused by scattering from plasma wave**
  - Matching peaks observed at $f_+ > 0$ and $f_- < 0$ where $f_- = -f_+$
- **DBS scatters from k_θ = 1.2 cm^{-1} ⇒ peak is high-k wave: cyclotron harmonic wave or electrostatic wave**
  - k_θ too large for Alfvén wave: ω/v_A~0.4 cm^{-1}

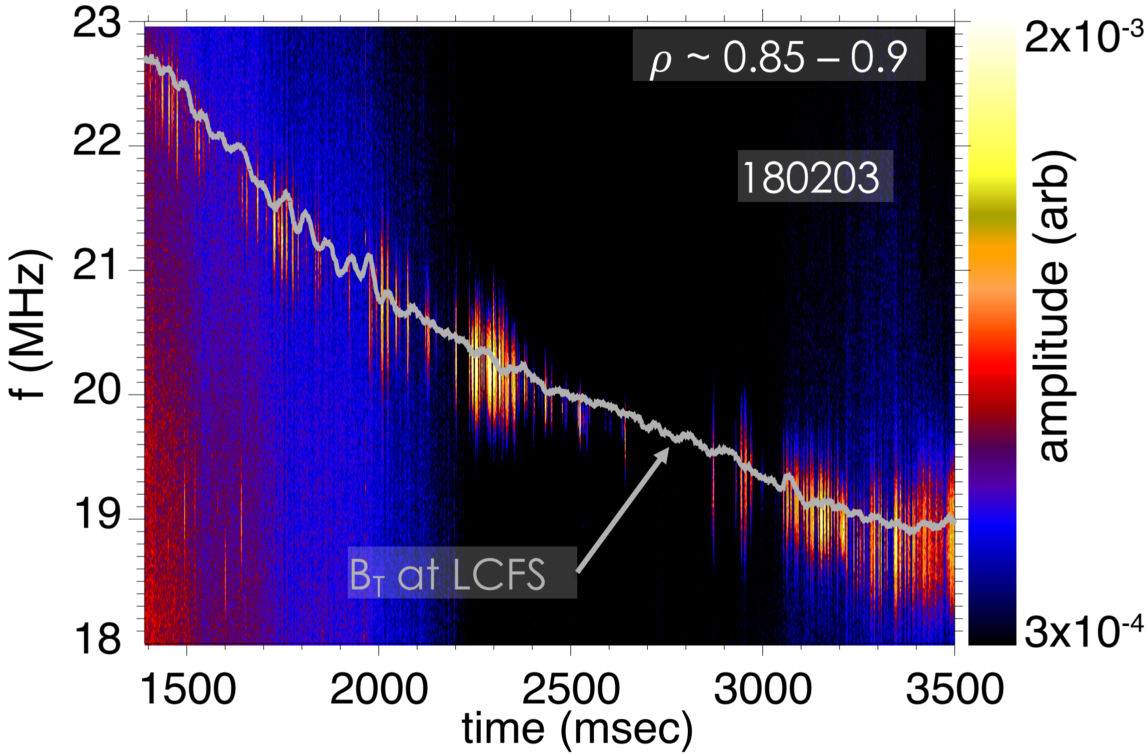
Unequal peaks at f_-, f_+ ⇒ high k wave



spectra are denoised by background subtraction

N.A. Crocker/63rd APS DPP/Nov. 8–12, 2021

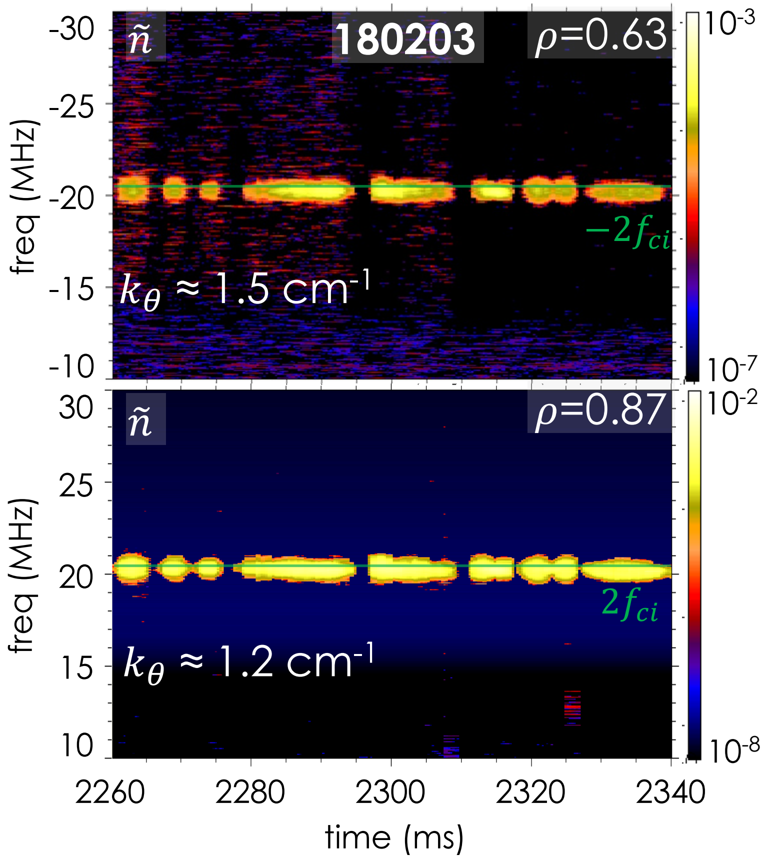
ICE frequency $\propto f_{ci}$ at last closed flux surface over large BT ramp



- $f \approx 2f_{ci}$ **at last closed flux surface (LCFS) during large** B_T **ramp,** $\Delta B_T/B_T$ **≈ 18 %**
- **destabilizing fast-ion resonance near LCFS (if** $k_{\|} \sim 0$**) ⇒ fast-ion loss boundary enhances anisotropy, drive?**

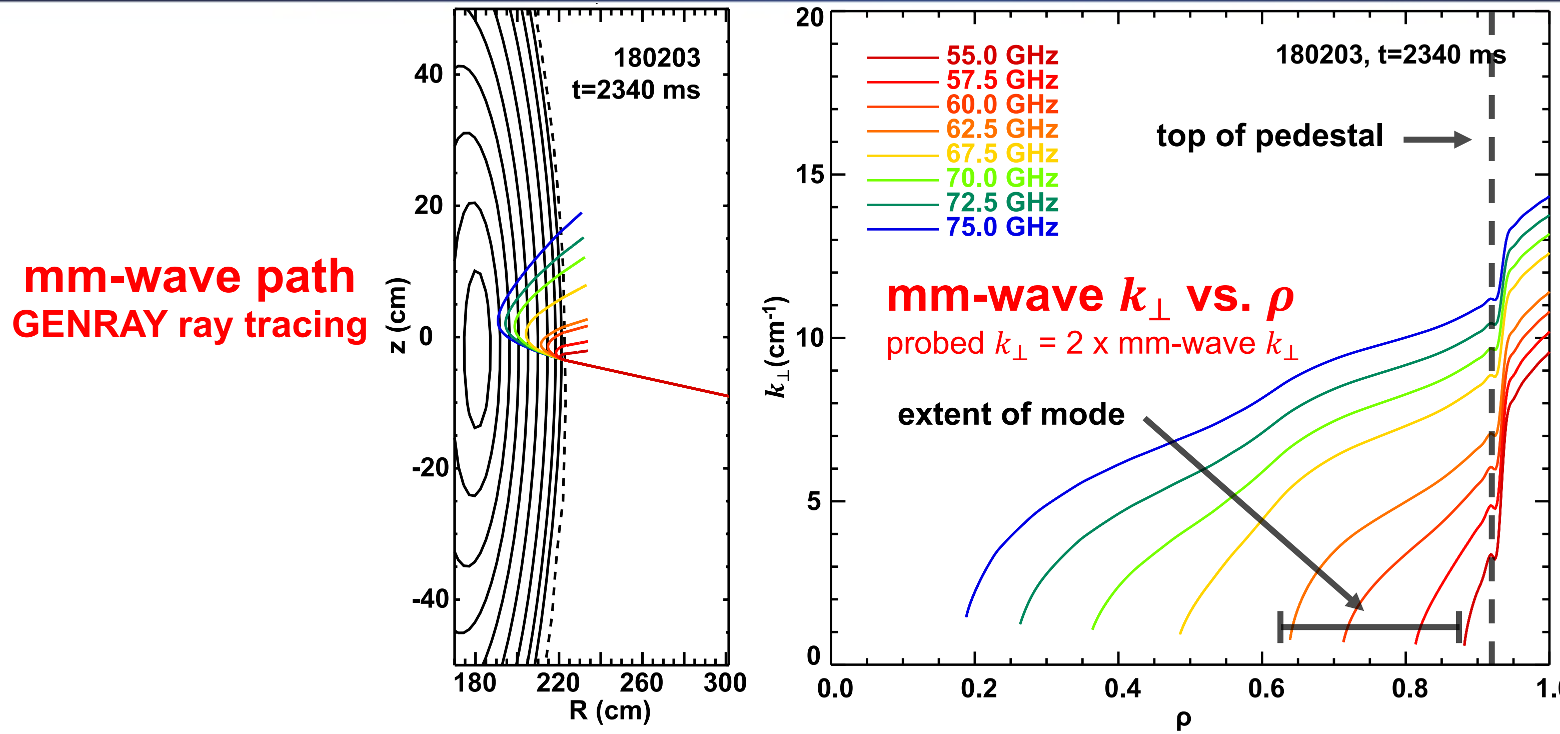
2nd harmonic ICE at pedestal-top observed to be radially broad

- **$2f_{ci}$ peak seen in outer 4 channels (out of 8): ρ = 0.63 – 0.87. Not seen ρ < 0.63**
  - same frequency all channels => "eigenmode" or propagating wave
  - strong peaks at $f = \pm 2f_{ci}$
  - asymmetric power consistent with scattering: $\tilde{n}(+2f_{ci}) \neq \tilde{n}(-2f_{ci})$
- **ρ = 0.63 – 0.87 $\Rightarrow$ radially broad: $\Delta R \gtrsim$ 7 cm = $a/6$ ($a = R_{midout} - R_0$)**
  - "$\gtrsim$" *because no measurements* $\rho > 0.87$
  - also, $\Delta R \gtrsim 2\rho_{fast}$



spectra are denoised by background subtraction

DBS coverage establishes radial extent and $k_\perp$ limits of pedestal-top 2nd harmonic ICE

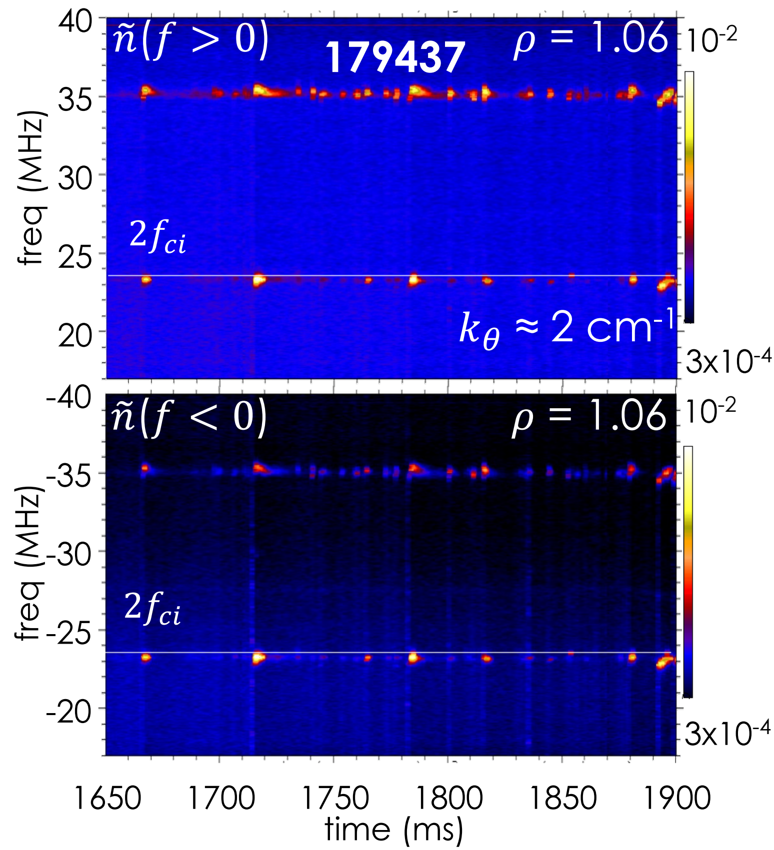


- **Mode not observed by high frequency channels (67.5 – 75 GHz) ⇒ mode not present ρ < 0.63**
  - All channels probe similar k_θ at cutoff (k_θ ~ 1.2 – 2.9 cm^{-1}) ⇒ wave seen by outer channels might be seen by inner channels if present in core
- **High frequency channels probe $k_\perp$> ~10 cm^{-1} in outer region ($\rho \geq$ 0.63): wave not detected ⇒ wave $k_\perp$< ~ 10 cm^{-1}**

2nd & 3rd harmonic high-k ICE observed in H-mode scrape off layer (SOL)

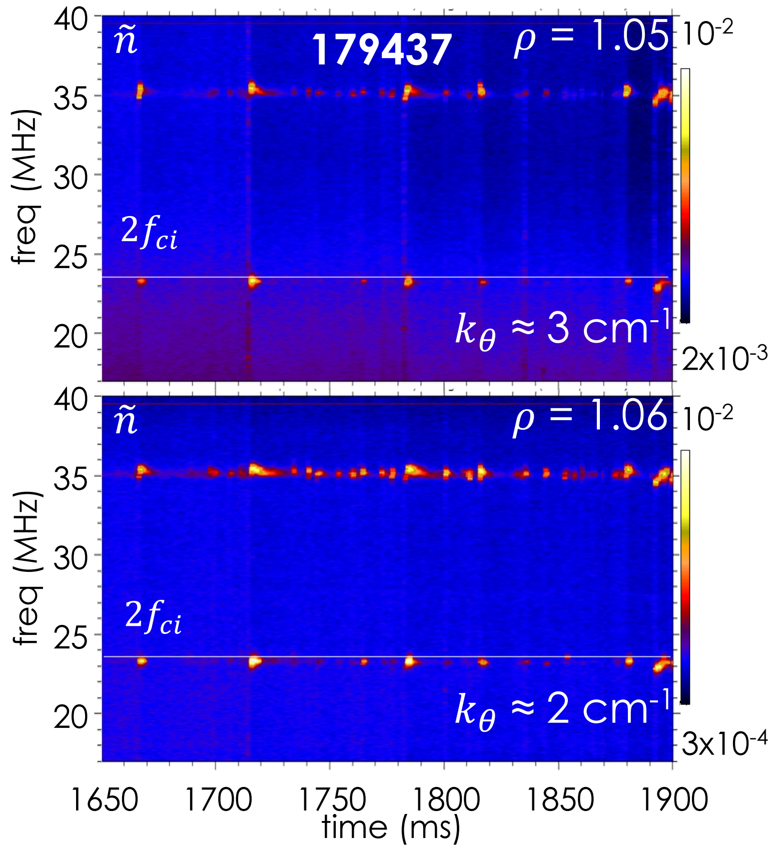
- **Deuterium H-mode**
  - R_{midout}= 2.27 m, R_0 = 1.73 m
- **$\tilde{n}$ measured at ρ=1.06 = SOL**
- **$\tilde{n}$ peaks at ±23,±35 MHz ~ ± $2f_{ci}$,$3f_{ci}$**
  - ρ_{fast} ~ 2 cm (species: D)
  - f_{ci} ≈11.8 MHz, v_A ~ 1.2 x 10^7 m/s
- **Peaks are caused by scattering from plasma wave**
  - Matching peaks at $f = f_+ > 0$ and $f = f_- < 0$ where $f_-= -f_+$
- **DBS scatters from k_θ = 2 cm^{-1} ⇒ peak is high-k wave: cyclotron harmonic wave or electrostatic wave**
  - k_θ too large for Alfvén wave: ω/v_A~0.1 – 0.2 cm^{-1}

Unequal peaks at f_-, f_+ ⇒ high k wave

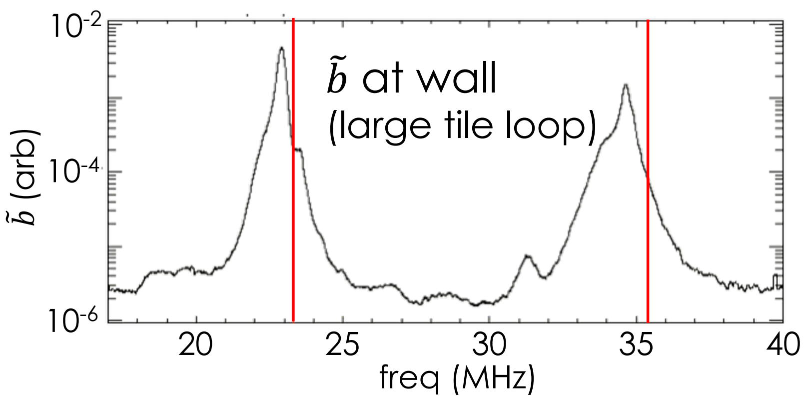


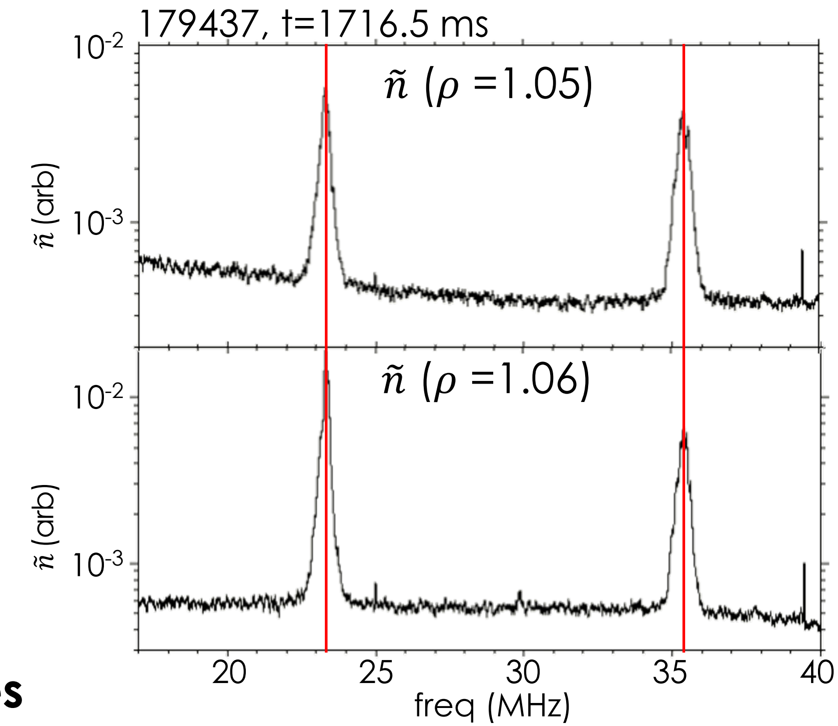
ICE in SOL observed to be radially extended

- $2f_{ci}$, $3f_{ci}$ **peaks observed on 2 channels:** ρ **= 1.05, 1.06**
  - same frequency all channels => "eigenmode" or propagating wave
  - strong peaks at $f = \pm 2\boldsymbol{f_{ci}}$
  - asymmetric power consistent with scattering: $\tilde{n}(+2\boldsymbol{f_{ci}}) \neq \tilde{n}(-2\boldsymbol{f_{ci}})$
- ρ **= 1.05, 1.06** $\Rightarrow \tilde{\boldsymbol{n}}$ **spatially extended:** $\Delta R \gtrsim$ **3/4 cm**
  - *"≳" because only 2 channels available*



Distinct differences in DBS and Magnetic SOL ICE spectra





- **$2f_{ci}$, $3f_{ci}$ peaks also observed in $\tilde{b}$ (tile loops) at wall**
- **$\tilde{n}$ and $\tilde{b}$ spectra show distinct differences**
  - $\tilde{b}$ peak f lower than $\tilde{n}$ peak f by ~ ½ MHz
- **$\tilde{n}$ modes not seen by tile loops on wall =>**
  - DBS sensitive to high-k waves which may attenuate before reaching tile loops
  - Tile loop probably sees fast Alfvén waves with long wavelength not detected by DBS: $\lambda = v_A/f \gtrsim$ 50 cm

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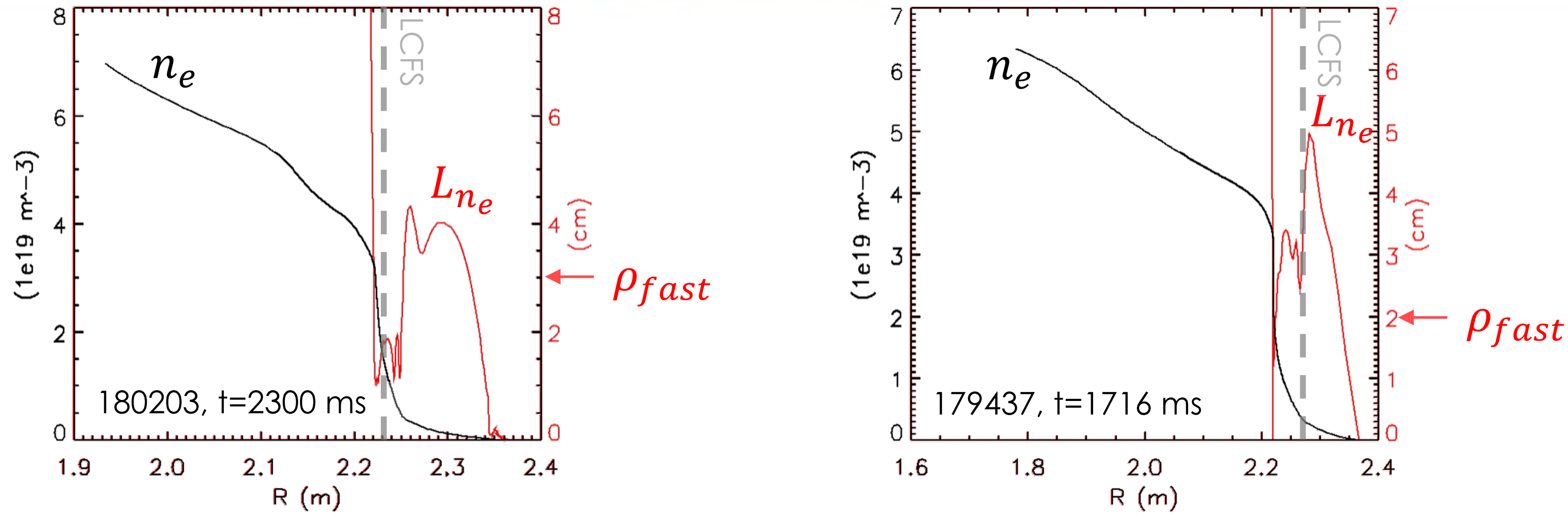
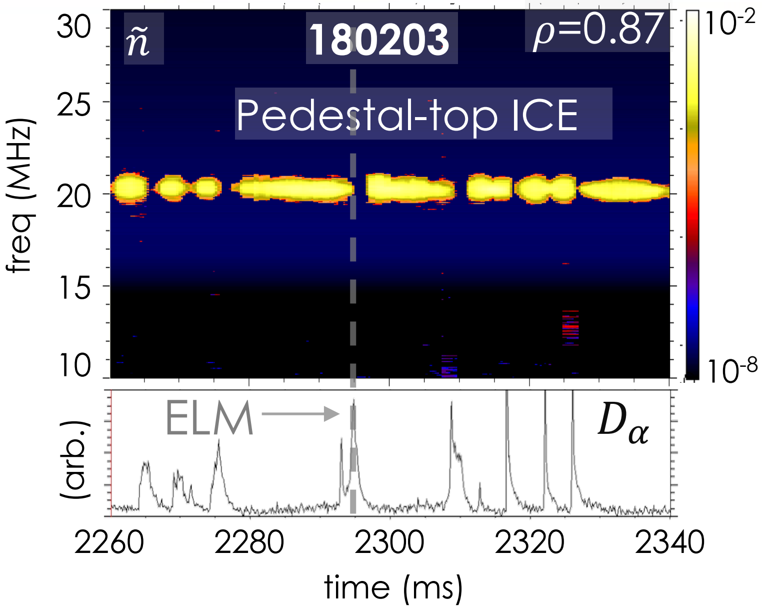
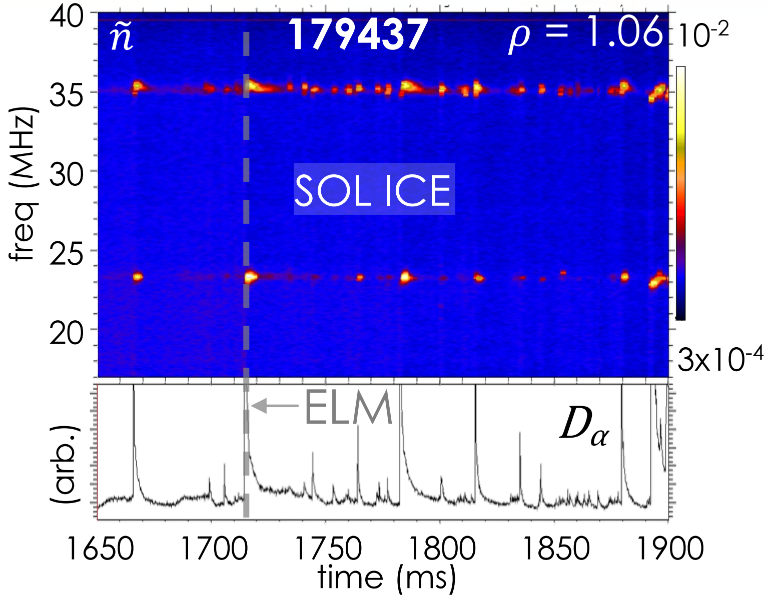
Strong density gradient may play role in ICE mode characteristics and instability



- **Strong density gradient at LCFS ($\rho_f/L_{n_e} \gtrsim 1$) may contribute to instability and mode characteristics – L_{n_e}~ρ_{fast}**
  - see ion cyclotron drift instability ([Mikhailovskii and Timofeev, Zh. Eksp. Teor. Fiz. 44, 912 (1963)], [Hendel and Yamada, PRL 1974])
- **Proximity to separatrix ⇒ loss cone ⇒ maybe important to instability**
  - see drift-cyclotron loss-cone instability ([Stix, *Waves in Plasmas*, AIP, New York, 1962 p. 436],[Farmer and Morales, NF 2016])
- **see discussion in [Dendy, PoP 1994 p. 3407] and refs. therein**

Edge ICE stability observed to be influenced by ELMs, consistent with fast-ion drive and fast-ion ejection by ELMs





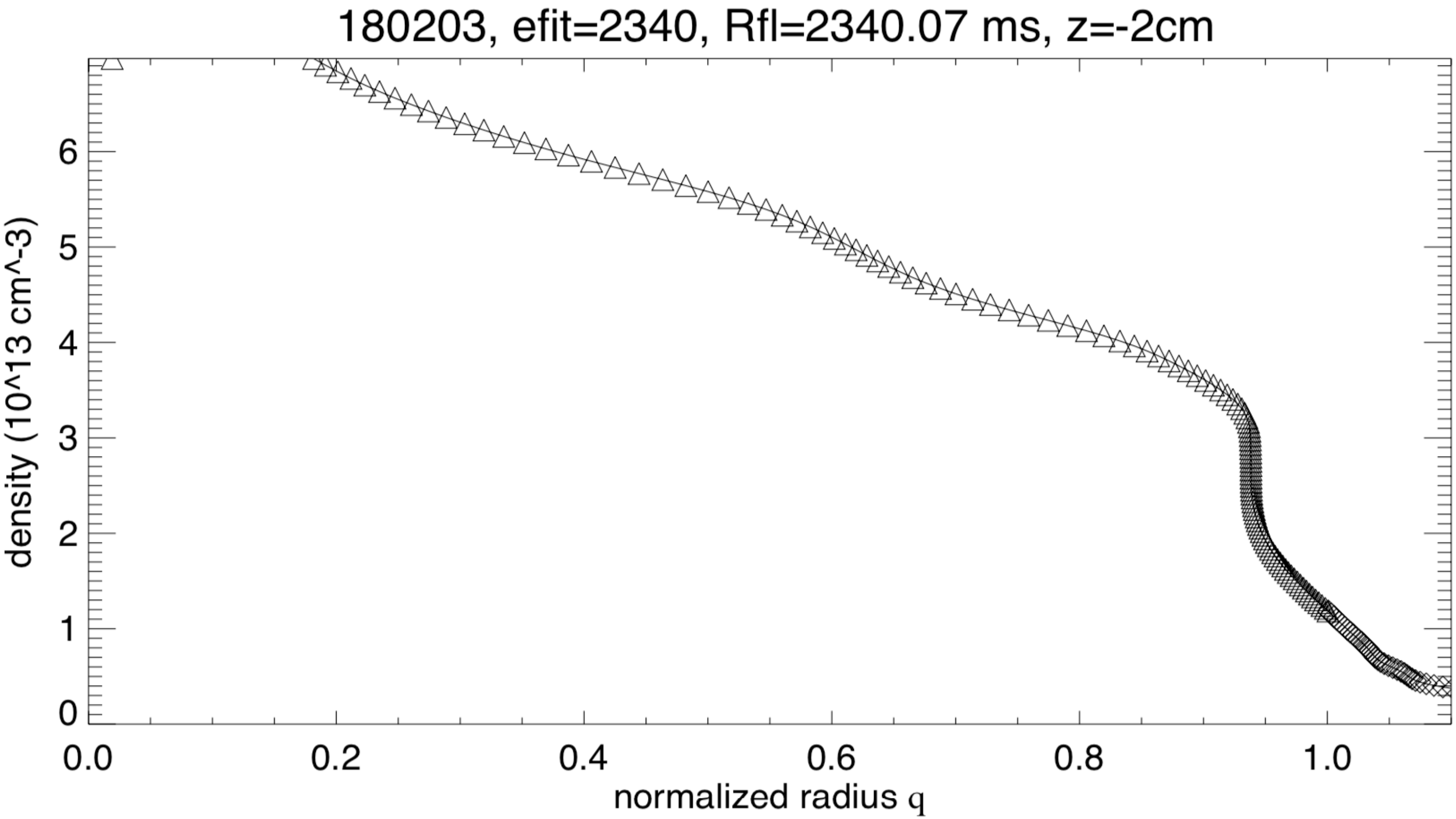
- **ELMs eject fast ions from the edge** [M. García-Muñoz, NF 2013]
- **Pedestal-top ICE amplitude transiently damps during ELMs (D_α spikes) ⇒ consistent with depletion of edge fast-ions that excite the ICE by ejection** [Cottrell NF 1993]
- **SOL ICE amplitude transiently jumps during ELMs (D_α spikes) ⇒ consistent with excitation by ejected fast-ions passing through SOL** [S. G. Thatipamula, PPCF 2016],[K. E. Thome, NF 2019]

Conclusions

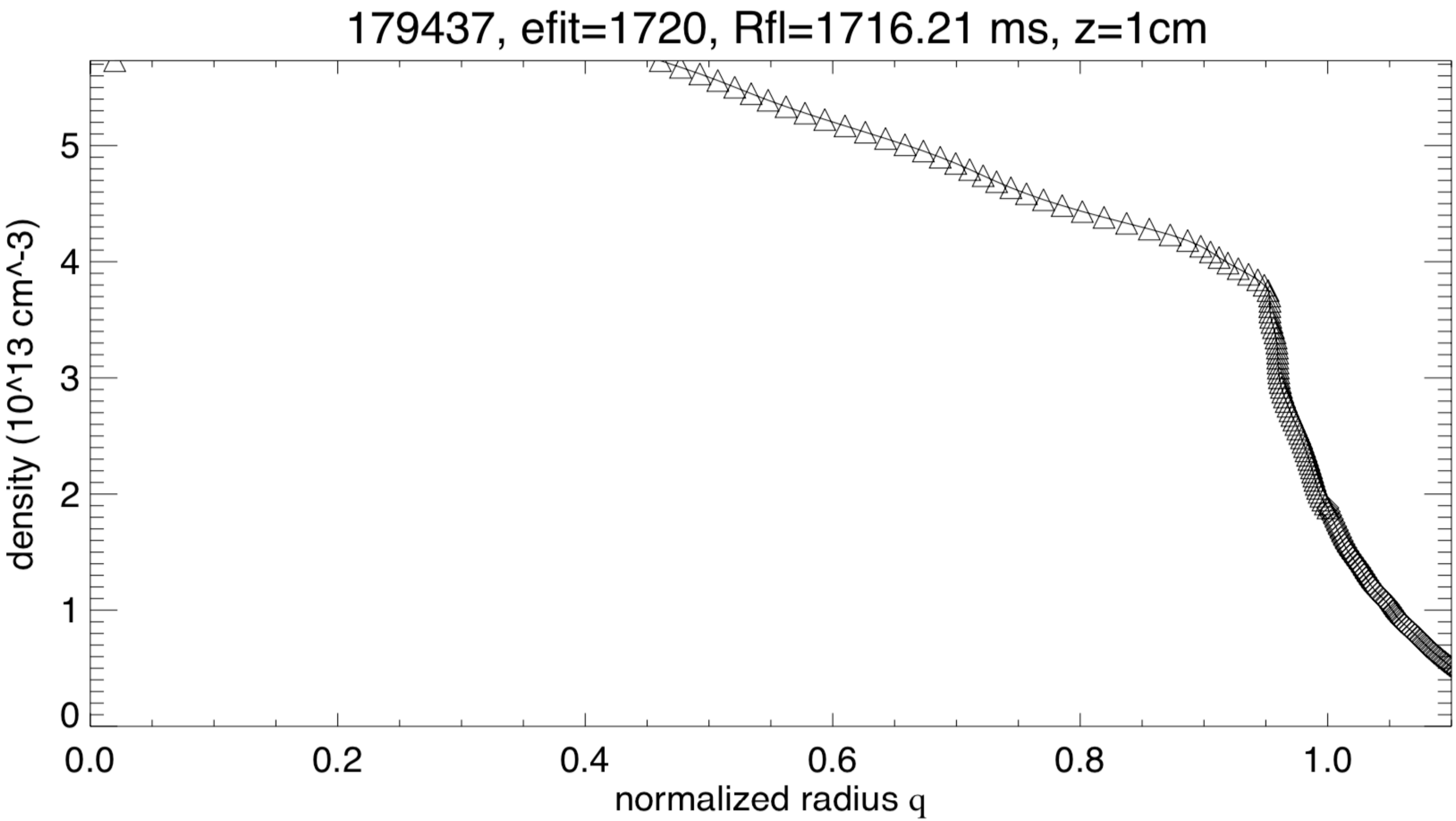
- **DBS measurements show ICE $\tilde{n}$ at $2f_{ci}$ & $3f_{ci}$ in the edge of DIII-D plasmas, at the top of the pedestal and in the SOL.**
  - Edge magnetic also show ICE $\tilde{\boldsymbol{b}}$ at $2f_{ci}$ & $3f_{ci}$ but the observed modes not the same as those observed by DBS
- **The observed ICE $\tilde{n}$ is shown to be high-k cyclotron harmonic waves or electrostatic waves**
- **The ICE $\tilde{n}$ is shown to be radially extended, consistent with eigenmode or propagating wave:**
  - SOL: $\Delta R \gtrsim$ ¾ cm
  - Top of pedestal: $\Delta R \gtrsim$ 7 cm ≈ $a/6$, ≈ $2\rho_{fast}$
- **The stability of the ICE $\tilde{n}$ is influenced by ELMs consistent with drive by fast-ions and fast-ion ejection by ELMs**
    - SOL: $\tilde{n}$ transiently excited during ELM as ejected fast-ion pass through
    - Pedestal-top: $\tilde{n}$ transiently damped during ELM as edge fast-ions depleted

Backup Slides

Density profile for pedestal-top ice case



Density profile for SOL ICE case



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Preview of conclusions

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  - Edge magnetic also show ICE $\tilde{\boldsymbol{b}}$ at $2f_{ci}$ & $3f_{ci}$ but the observed modes not the same as those observed by DBS
- **The observed ICE $\tilde{n}$ is shown to be high-k cyclotron harmonic waves or electrostatic waves**
- **The ICE $\tilde{n}$ is shown to be radially extended, consistent with eigenmode or propagating wave:**
  - SOL: $\Delta R \gtrsim$ ¾ cm
  - Top of pedestal: $\Delta R \gtrsim$ 7 cm ≈ $0.2a$, ≈ $2\rho_{fast}$
- **The stability of the ICE $\tilde{n}$ is influenced by ELMs consistent with drive by fast-ions and fast-ion ejection by ELMs**
  - SOL: $\tilde{n}$ transiently excited during ELM as ejected fast-ion pass through
  - Pedestal-top: $\tilde{n}$ transiently damped during ELM as edge fast-ions depleted